Frost Quake Events and Changing Wintertime Air Mass Frequencies in Southeastern Canada

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Abstract

In recent winters (2013/14, 2014/15), numerous frost quake occurrences were reported from southeastern Canada, specifically in southern Ontario and Quebec provinces. A frost quake is defined as the unexpected, fast-action cracking at the surface of water- or ice-saturated permeable material following a rapid temperature drop to subfreezing conditions. Prior to the intrusion of cold air, rapid ground saturation and little-to-no snow cover are two necessary meteorological characteristics for a frost quake. A 60-year analysis of wintertime air mass frequencies is completed for the city of Toronto, located in southern Ontario, to determine if the latest frost quake events are associated with large-scale atmospheric pattern changes. Warmer, moister air masses have increased in comparison to colder, drier polar air masses. The number of thaw days (i.e. winter days the temperature is ≥ 0°C) has increased by ~14% inferring an incremental rate of one additional day, per five winters, that reaches thaw conditions. An increase in non-measurable snow depth days correlates well with the increased number of thaw days. These winter surface conditions, which occur more frequently prior to cold air intrusions in the present climate, likely have contributed to the surge in recent frost quake events in southeastern Canada.

Keywords: Frost Quakes; Canada; Spatial Synoptic Classification; Air Mass; Wintertime; Climatology

1. Introduction

A *cryoseism*, meaning *cold-produced, earth vibration*, is produced by the abrupt, non-tectonic cracking of frozen material at the Earth's surface. There are two types of cryoseisms: *ice quakes*, which are related to the ice rifting on the surface of water, such as glaciers or lakes (e.g., Neave and Savage, 1970; Burke, 2004; Walter *et al.*, 2008), and *frost quakes*—cryoseisms that are associated with fracturing of saturated rock or soil on a landmass (Lacroix, 1980; Nikonov, 2010). For a frost quake to transpire, frozen permeable rock or soil expands when the surface temperature drops to well-below freezing, a drop of about 16°-22°C to a low temperature of ≤ -15°C (Battaglia and Changnon, 2016), which increases the stress on its local surroundings and may relieve the pressure in an explosive form (Fig. 1). The end result of the pressure being violently released is a single fracture on the ground and a boisterous booming noise. Frost quakes (henceforth, FQ) are the focus of this study.

Numerous FQs were reported in modern winter seasons (2013/14, 2014/15) in the eastern two-thirds of North America (e.g., Draxler, 2014; Brown, 2015). The University of Toronto—Scarborough Climate Lab (UTSC Climate Lab, 2015) created a map of reported FQs from the recent two winters (Fig. 2). The map indicates a large number of FQ reports are located in southeastern Canada, specifically in southern Ontario and Quebec provinces, near highly populated cities such as Toronto, Montreal, Ottawa, and Calgary, while other reports are located in the U.S. Midwest and Northeast. The majority of the FQ occurrences were reported in Canada compared to the U.S.

Meteorological variables, specifically temperature and snow depth (i.e. the average height of old snow and ice on the ground), play a significant role in a FQ occurrence. Water from liquid

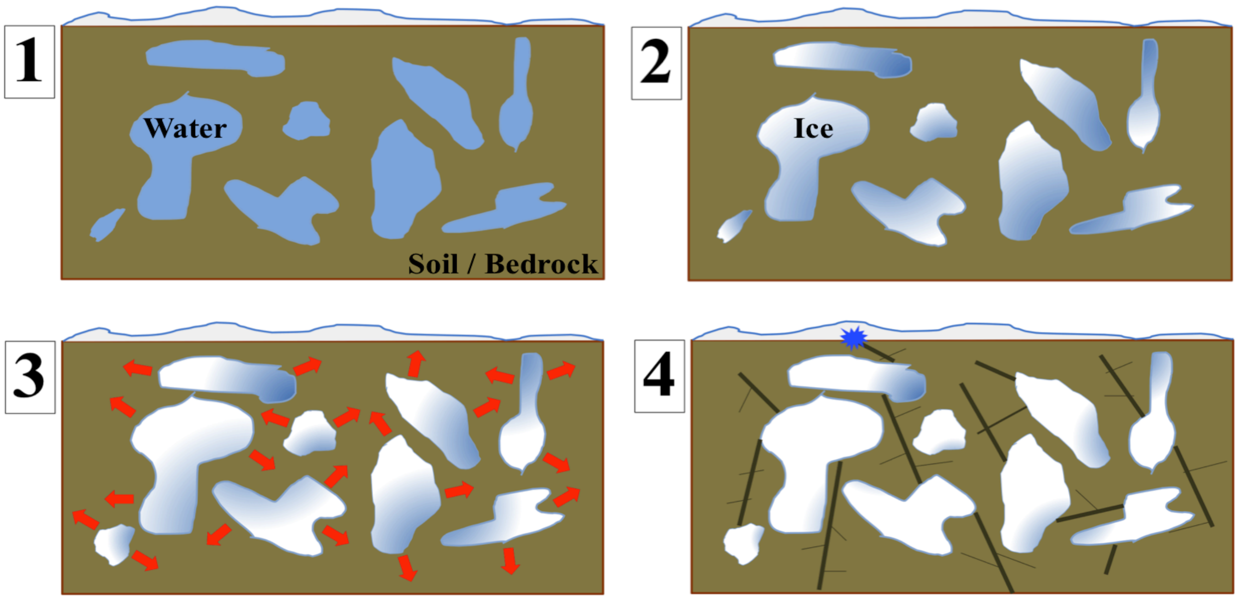

Fig. 1: The general process for a frost quake formation. Panel [1]: Water saturates the soil or bedrock near the surface from thaw, precipitation, or flooding and is essentially "trapped" in the ground. Panel [2]: As the surface temperature cools, the water in the subsurface freezes. Panel [3]: The ice begins to expand as the temperature continues to cool (as shown by red arrows) and increases the pressure on the surrounding soil/bedrock. Panel [4]: The stress from the expansion of ice is too much and causes fractures to form that can create a loud noise and occasionally ground shaking.

precipitation, snowmelt, or nearby flooding is necessary to saturate the ground prior to freezing (Lacroix, 1980). Once the surface temperature is below freezing, the "trapped" water beneath the surface can freeze and begin to increase pressure on its surroundings, which may eventually lead to a FQ event. Has the assemblage of atmospheric and surface characteristics that are essential for a FQ, such as thaw temperatures (≥ 0°C) and water availability prior to a dramatic cold air intrusion, become more likely to transpire in recent years?

The goal of this research is to complete an analysis of long-term, 60-year (1954/55-2013/14) trends in overall weather pattern frequency (i.e. air masses) and surface meteorological conditions to investigate if the recent FQ episodes that occurred in southeastern Canada are associated with changing winter climate conditions. The methods of this study focus on the general weather circumstances in the city of Toronto, located in southern Ontario, and tests whether there is an association between changing wintertime air mass frequencies and the surface meteorological characteristics, specifically temperature and snow depth, associated with the occurrence of FQs.

2. Data and Methods

2.1. Reported frost quake locations

Little information is known about FQs due to their rarity in nature. One of the first recognized accounts of a frost-prompted surface crack was published in 1819. Edward Hitchcock, an American geologist, reported a singular disruption (i.e. one large crack separate from any other) on the surface in Deerfield, Massachusetts (Hitchcock, 1819). Neighbors of the disruption reported hearing a loud "bang" noise in the early morning hours prior to sunrise. Hitchcock concluded the disruption was caused by water-saturated ground, likely from a nearby stream flooding prior to a significant drop in surface temperature, which froze, placed a large amount of stress on its surroundings, and formed the fracture associated with the lurid noise.

More than a century-and-a-half later, Andrew V. Lacroix of the Western Geophysical Corporation in Westboro, Massachusetts compiled previous published and unpublished reports of FQs since Hitchcock's publication (Lacroix, 1980). This was done to discriminate between earth-

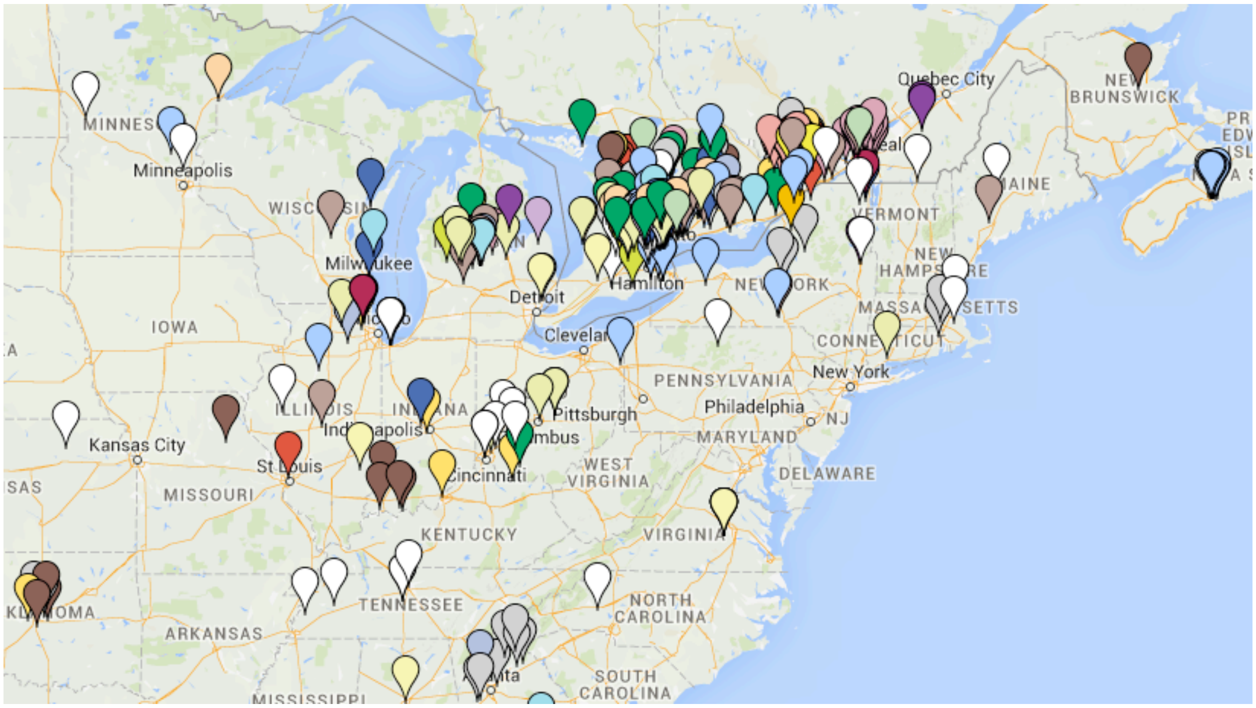

Fig. 2: A snapshot of frost quake locations from the combined 2013/14 and 2014/15 winter seasons in the eastern two-thirds of North America. The marker colors represent specific temporal dates of each event over the two winters. Most reported frost quakes occurred in the winter months (DJF). A large number of frost quakes were reported in southern Ontario and Quebec provinces compared to the general distribution of occurrences. [Credit: UTSC Climate Lab (2015:tinyurl.com/neft8kp) and ©GoogleMaps.]

quakes that are caused by tectonic activity and cryoseismic events that are triggered by the fast-action freezing of ice in permeable rocks and soils. Lacroix (1980) determined that seismic monitoring stations infrequently measure the FQ "rumble" since the fabricated vibrations are subject to small, localized areas (i.e. the *felt* region of the fracture location). Lacroix (1980) concluded that a FQ clatter is similar to an earthquake with an intensity IV on the Modified Mercalli Intensity Scale. Adjacent persons to a FQ occurrence typically report a sufficient bursting noise and sometimes, but not as often, ground shaking from the blast that may resemble a large vehicle striking a building. The locations of FQ happenings are thus resulted from public accounts of, or similar to, "a loud, booming noise" instead of instrumentation in the affected, *felt* area.

Modern FQ locations are determined by social media statuses (i.e., *Facebook, Twitter*) in which a person of the public was in the FQ *felt* area and the digital account pinpoints the report to a geographic location (e.g., Draxler, 2014; Brown, 2015). It is, however, difficult to assess whether a FQ report was from the actual phenomenon or from public misinterpretation of a different manifestation. For instance, the expansion and contraction of a house during wintertime temperature changes could produce an intense clamor that may be misinterpreted as a FQ. Since the focus of this study is not on one specific FQ event, and the UTSC Climate Lab map of reported locations (see Fig. 2) is one of the limited collations available on the spatial and temporal occurrences in eastern North America (i.e. there is no long-term record of FQs for a region), it is assumed that any misrepresented modern FQ reports is not expected to affect the results from the methods presented.

2.2. Spatial synoptic classification air mass data

The numerous recent FQ reports in southeastern Canada may be associated with changing trends in overall weather conditions. An approach to determine whether the overall weather pattern for a particular region is changing, instead of fo-

cusing on one meteorological variable such as temperature, is to investigate air mass frequencies (e.g., Sheridan and Kalkstein, 2010; Hondula *et al.*, 2014). An air mass is roughly defined as a large body of air that has relatively uniform humidity and temperature characteristics. The frequencies of air masses have been used to determine statistical changes in the U.S. climate from 1948 to 2005, specifically the increase in warm, humid air at the expense of cold, dry air (Knight *et al.*, 2008). Transitional days, which occur between changes in air masses and do not conform to one type of uniform body of air, were found to be decreasing from a seasonal and regional analysis of the continental U.S. (Hondula and Davis, 2011a, 2011b). The results suggested there might be a consistency with poleward moving storm track changes and a decrease in weather frontal passages in Canada (McDonald, 2011). Air mass studies have also investigated the potential effects on human health from warming trends in Canadian cities (Hondula *et al.*, 2014; Vanos and Cakmak, 2014).

An all-inclusive method of air mass categorization is the spatial synoptic classification (SSC) system developed by Sheridan (2002) that accounts for general seasonal variability based on the climate distribution expected for a particular time of year (e.g., Sheridan and Dolney, 2003; Davis *et al.*, 2010). The SSC uses "sliding seed days" that represent predictable and observed meteorological conditions at each location throughout the year for one type of air mass (Sheridan, 2002, 2014). To select seed days for each season and location, typical meteorological characteristics are quantified, and ranges specified to indicate maximum values of atmospheric variables between weather types. The meteorological conditions used include surface weather observations of cloud cover, moisture, air temperature and pressure, wind velocity, and the duration of the air mass. Days that satisfy the essential criteria are then extracted with confirmation and completed subsequently for the given air mass type in the SSC dataset. Each location thus has an individualized set of weather types from the daily-characterized air mass that can be used to assess weather conditions over time. Each air mass type from the SSC is listed and described in Table 1. Since temperature

Table 1: Air mass types and transitional day category used in SSC scheme. The descriptions of each air mass type are from Sheridan (2002, 2014), Knight *et al.* (2008), Davis *et al.* (2010), and Vanos and Cakmak (2014).

Air Mass Type	Air Mass Description
Dry Polar (DP)	Cold air mass generally advected from polar regions around a cold-core anticyclone. Typically associated with lowest temperatures observed in a region for a particular time of year with clear, dry conditions.
Dry Moderate (DM)	A mild to dry air mass that is often found with zonal flow in the mid-latitudes. Arises when traditional DP or MT air mass has been advected far from its source and has been considerably modified.
Dry Tropical (DT)	The hottest and driest conditions of any air mass in which the body of air has been advected from either a desert region or produced by rapidly descending air.
Moist Polar (MP)	An air mass with conditions of cloudy, humid, and cool that was transported inland from a cool ocean or as a result of frontal overrunning from the south of the region.
Moist Moderate (MM)	A warmer air mass and more humid than MP that appears in a zone south of MP. This is an area of overrunning, but with the front responsible much nearer to the region. MM can also appear when high cloud cover suppresses the temperature of an MT air mass.
Moist Tropical (MT)	A very warm and humid air mass that is typically found in warm sections of mid-latitude cyclones or in a return flow on the western side of an anticyclone.
Transitional Day (TR)	These days are defined as those in which one weather type yields to another based on a large shift in pressure, dew point, and wind over the course of that specific day. These days do not fit the categories of any of the other air mass types. If all parameters are 1.3 standard deviations greater than the period mean, then the day is classified as TR. These days commonly have passing warm or cold fronts associated with mid-latitude pressure systems.

is the dependent variable associated with the long-term fluctuations in weather patterns, changes in air mass frequency is therefore used in the following analyses and discussion to determine if deviations in large-scale atmospheric patterns are associated with the meteorological characteristics for FQ events.

2.3. Relationship of winter air masses to surface weather conditions

The air mass data was collected for the winter seasons (DJF) over a 60-year period from 1954/55 to 2013/14 for the city of Toronto in southern Ontario. This site was selected among other available SSC locations in southeastern Canada because Toronto experienced the majority of FQ reports juxtapose to its geographic location (see Fig. 2). Air mass frequency trends were produced using standard ordinary least squares (OLS) regression. The changing air mass frequencies over time were compared using the slope of the linear regression that represents the relative change of each air mass per year. If in the event that greater than 10 days of data were missing from a winter season for a study site, the year was excluded from the analysis. Toronto has 90% of available years of air mass data from the 60-year period.

From the seven air mass types (Table 1) that are used to classify the overall weather conditions, two air mass types are not used in this study. Dry tropical (DT) and moist tropical (MT) air masses are very infrequent or non-existent in Canadian winter seasons. Although DT and MT air masses can protrude and have an impact on the cities in southern Ontario, the total number of days in which these tropical air masses effect the wintertime weather situations in Toronto is deemed insignificant for this study.

Pearson correlation analyses were completed to determine how one air mass type changed relative to each other. These correlations demonstrate the relative change of dry versus moist air masses for Toronto. The frequency of daily temperature extremes per winter and change in air mass types were correlated to determine the impact of each air mass on the maximum surface temperature. The temperature dependent change was quantified by collecting the number of days per winter season in which the maximum daily temperature was equivalent to or exceeded the freezing point of water (i.e. $T_{max} \geq 0$°C) from the Canadian Climate Website (climate.weather.ga.ca). These days are, henceforth, called *thaw days*.

A linear OLS regression for thaw days was constructed similar to the air mass data to determine relative change of ≥ 0°C conditions in Toronto. Days when snow depth = 0 cm was run in a Pearson correlation with thaw days (≥ 0°C) to determine how well these two variables are related. Days when there was no measurable snow cover on the ground in Toronto was collected from the Canadian Climate Website.

All OLS regression slopes and Pearson correlation analyses were deemed significant at a confidence level of < 0.05. Each dataset was tested for collinearity and were found to have a linear relationship with the independent variable time (i.e. years). The regressions and correlations that are considered significant are noted in the results in the following sections.

3. Results and Discussion

3.1. Descriptive Statistics

An initial investigation of the descriptive statistics for each dataset from the 60-year analysis for Toronto is provided in Table 2. On average, the most frequent air mass types are DP and MP, while the least frequent air mass type is DM. The DM and MP air mass datasets have the greatest range from the SSC data. MM air mass days and TR days have the smallest range of the SSC datasets. The dataset for days with no measurable snow depth has a large range from as little as 5 days to as much as 78 days.

3.2. Air Mass and Transitional Day Trends

The regression slopes for the air mass types are displayed in Table 3. An initial investigation of statistical significance was done to rule out insignificant datasets. Three of the five air mass frequency trends were statistically significant: DM, MP, and TR. The DP and MM air mass frequency datasets did not exhibit significant trends.

Fig. 3 shows the plots for all five SSC air mass trends. The 60-year trends generally demonstrate an increase in DM air mass frequencies and a decrease in MP air masses and TR days from

Table 2: Statistic diagnostics of the collected datasets for the city of Toronto. The datasets include dry polar (DP), dry moderate (DM), moist polar (MP), moist moderate (MM), and transitional day (TR) air mass trends from the SSC, thaw days ($T_{max} \geq 0°C$), and days with no measurable snow on the ground (= 0 cm).

	Mean	Median	Std. Error	Max	Min	Range	Skew	Kurtosis
DP (days)	23.6	24.0	6.3	37	10	27	-0.39	-0.33
DM (days)	9.8	7.0	8.7	37	0	37	1.43	1.65
MP (days)	28.1	28.0	8.8	48	10	38	0.35	-0.29
MM (days)	15.1	15.0	5.3	31	5	26	0.37	0.47
TR (days)	11.9	11.0	5.1	26	2	24	0.89	0.69
Thaw days ($T_{max} \geq 0°C$)	31.3	29.0	10.1	57	13	44	0.57	0.05
Snow depth = 0 cm (days)	35.6	34.0	17.8	78	5	73	0.36	-0.66

the 1954/55 to 2013/14 winter seasons in Toronto. The DP and MM air mass frequency trends show a slight decrease over the six decades, but both datasets have a larger variability compared to the MP air mass trend.

The negative slope for DP of -0.06 indicates a decrease in cold, dry polar air in Toronto that is consistent with recent literature on air mass frequency changes in Canada (Vanos and Cakmak, 2014). This slope indicates that the number of DP air mass days in Toronto's winter has decreased by ~4 days over the six decades, or a ~4% decrease of all days in the winter season. The slope parameter suggests that there has been a small decrease in the total cold air advected into southern Ontario from the polar source region.

The DM trend has a positive slope implying a strong increase in milder air compared to dry polar air (DP air masses) in Toronto's winter. This is similar to the analysis of an expected increase in atmospheric moisture in Canada compared to a half-century ago (Vincent *et al.*, 2007). The slope of +0.32 suggests a ~21% increase in moderately dry days (or ~19 days) since the 1954/55 winter season. The positive trend indicates that DP air advected from the north and west during the winter months is occurring less frequently today than in previous decades, possibly from a latitudinal increase in zonal flow and storm track changes (e.g., Fu *et al.*, 2006; McDonald, 2011).

Regression analysis for MP air masses in Toronto implies a strong decrease in the frequency of moist air masses from polar source regions. This finding is similar to previous studies conducted on the changing air mass frequencies of milder and moist air that are being advected more from southerly, warmer regions in comparison to northerly, colder areas (Vincent and Mekis, 2006). The slope of -0.23 suggests a ~15% decrease of days in Toronto in which an air mass is advected inland from a geographic body of water or by frontal overrunning from the south. This could be associated with possible storm track changes and increased zonal flow (e.g., Fu *et al.*, 2006) associated with the increase in DM air masses as stated above.

Table 3: Regression slopes and R^2 values for each air mass type over the 60-year period from 1954/55 to 2013/14 winter seasons. Standard deviations are given in parentheses for slope parameters. [*Indicates statistical significance of < 0.05.]

Air Mass Type	Slope Parameter (Std. error)	R^2
DP	-0.06 (0.05)	0.03
DM	+0.32* (0.05*)	0.40*
MP	-0.23* (0.06*)	0.21*
MM	-0.02 (0.04)	0.01
TR	-0.07* (0.04*)	0.06*

The MM air mass trend has a slight negative slope of -0.02 that is indicative of a ~1% decrease (~1 day) of moist air days compared to dry-to-mild air masses. This negative slope, although small and perhaps irrelevant to the large-scale atmospheric changes as compared to the other air mass regressions, suggests humid air that is being advected from the south is not able to infiltrate southern Ontario by overrunning the cooler, drier air masses from the north (similar to the MP air mass trend).

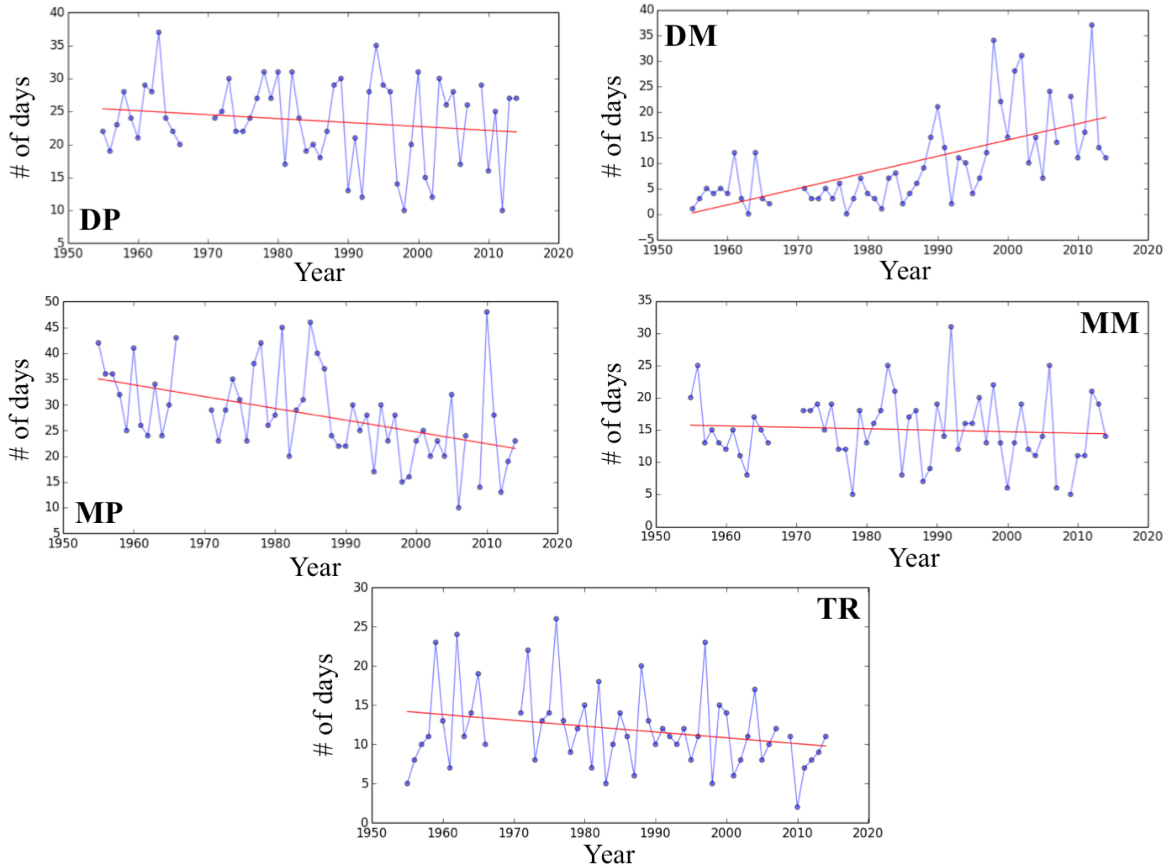

Fig. 3: The 60-year wintertime trends for dry polar (DP), dry moderate (DM), moist polar (MP) and moist moderate (MM) air mass frequencies, and transitional days (TR) for Toronto. Five winters were removed from the data: 1966-1970 and 2007-2008 (>10 days missing). The trend line plotted on each figure is the calculated slope parameter for each air mass regression. The slope parameter values are provided in Table 3.

The trend for TR days shows a decrease with a negative slope of -0.07 (or ~4 less days compared to six decades ago) that is consistent with recent investigations of a decrease in annual transitional days in the U.S. (Hondula and Davis, 2011a, 2011b) and Canada (Vanos and Cakmak, 2014). The decrease in TR days may be occurring from weaker frontal systems (Kalkstein *et al.*, 1990), fewer frontal systems (e.g., McCabe *et al.*, 2001; Yin, 2005), or changes in latitudinal storm track locations associated with the movement of the jet stream (e.g., McDonald, 2011).

Overall, the air mass type trends indicate warmer air masses are increasing and colder air masses are decreasing in the total percentage of wintertime days in Toronto over the past six decades. These changes indicate that the number of thaw days should increase with time.

3.3. Dry vs. Moist Air Mass Correlations

Table 4 shows the Pearson correlation matrix for the SSC air masses (excluding transitional days, TR, which do not fit a definite air mass category). The DP air mass is negatively correlated with the other three air mass types implying a decrease in drier air in response to the increase of milder or more humid air masses in southern Ontario during the winter. The strongest correlations involve significant increases in DM and MM air masses compared to a decrease in DP, similar to

findings for the U.S. (Knight *et al.*, 2008) and Canada (Vanos and Cakmak, 2014).

The DM air mass has a negative correlation with MP air masses with a statistically significant correlation of -0.64 over the six decades. The DM air mass has a trivial positive correlation with MM air masses (+0.03). The MP air mass also had an insignificant correlation, yet negative, with MM air masses (-0.10). Overall, these correlations suggest mild to moderate air masses are advected into Toronto at the expense of drier air.

A reduction of dry and cold conditions, replaced by moist and warmer conditions, is consistent with patterns of both temperature (Coward and Weaver, 2004) and moisture (e.g., Robinson, 2000; Vincent and Mekis, 2006) increases in Canada. The increase of DM in Toronto in the wintertime, with a negative DP relationship, is in agreement with investigated Arctic trends (Kalkstein *et al.*, 1990). Held (1993) previously argued that the enhanced moisture is to be expected based on a warmer climate, which has a direct effect in the horizontal heat transported poleward. This moisture upturn could also be associated with storm track changes and a decrease in the number of low-pressure systems from the decline in TR days.

The increase in moist air masses indicates a higher probable annual precipitation amount for Toronto and, therefore, southeastern Canada (Vincent and Mekis, 2006; Kunkel *et al.*, 2013). Wintertime snowfall in Canada has decreased over the past half-century (Yagouti *et al.*, 2008) that tends to indicate an increase in liquid precipitation (Knight *et al.*, 2008). More liquid precipitation events, likely from an increase in the average surface temperature (especially with an increase in thaw conditions) and surge of moist air masses in comparison to the decrease in dry air, can recharge the subsurface more easily from rainfall or snowmelt.

3.4. Implications for frost quake events

FQs are likely to transpire when the surface temperature prior to an event is ≥ 0°C in order for the ground to undergo thaw and allow liquid water to penetrate the subsurface (e.g., Lacroix, 1980). MP and DP air masses are decreasing and DM air masses are increasing that suggests more frequent winter days with milder temperature. Since this is the case, the number of days when $T_{max} \geq 0$°C should be increasing over time

Table 4: Pearson correlation matrix of SSC air mass comparisons to demonstrate dry versus moist effects of southeastern Canada. Standard errors are provided in parentheses. [*Indicates statistically significant at confidence level of < 0.05.]

Air Mass Type	Dry Polar, DP	Dry Moderate, DM	Moist Polar, MP	Moist Moderate, MM
DP	1.00			
DM	-0.64* (0.17*)	1.00		
MP	-0.05 (0.19)	-0.64* (0.11*)	1.00	
MM	-0.41* (0.10*)	+0.03 (0.08)	-0.10 (0.08)	1.00

Fig. 4 is the number of thaw days per winter in Toronto for the 60-year trend. The slope parameter is +0.22, which is significant at the < 0.05 confidence level. This rate increases at approximately one extra day the $T_{max} \geq 0$°C per winter season about every five years. This is a ~14% increase (~13 additional days) of thaw days since the 1954/55 season. This is likely occurring from the increase in warmer air masses and fewer cold air masses during the winter. Although the goodness of fit of the regression is low ($R^2 = 0.146$), the data is still meaningful since it demonstrates there has been a gradual increase in warm winter days in Toronto. This may be related to the increase in average surface temperatures over the last century (e.g., Alexander *et al.*, 2006; Trenberth *et al.*, 2007; Knight *et al.*, 2008).

Table 5 shows the Pearson correlations for the air mass types (excluding TR) versus the number of thaw days per winter season. The DM air mass has the strongest correlation with thaw days. The 60-year trend in DM and MM are both positively correlated with thaw days, suggesting more days with milder air masses and an increase in thaw days. The increase in milder air masses occurs as trends for both in DP and MP, polar air masses, decrease over the 60-year period.

The surface temperature increase in Toronto as measured by the number of thaw days ($T_{max} \geq 0$°C) suggests that there is the opportunity for more ground recharge from precipitation or snowmelt (or flooding). FQs require the ground recharge in order for the subsurface to be filtrated with liquid prior to the surface temperature drop-

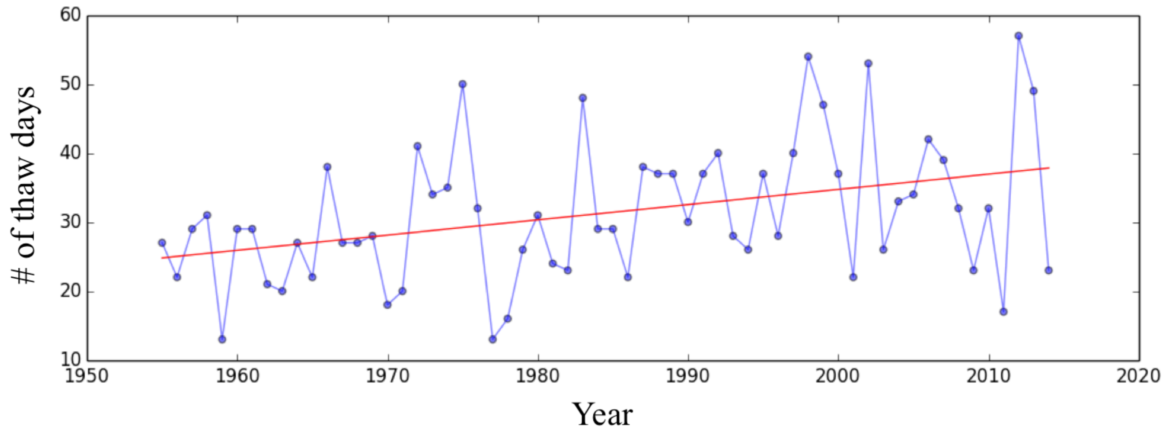

Fig. 4: The number of wintertime days when the daily maximum temperature (T_{max}) is ≥ 0°C for the 60-year analysis in Toronto. The calculated slope parameter from the regression is +0.22. The dataset is statistically significant at a confidence level of < 0.05.

ping to below freezing. The snow depth, which assists in recharging the ground during the wintertime, is an important meteorological characteristic that could affect FQ occurrences. The relationship of thaw days to the number of days with no measurable snow depth (= 0 cm) was determined (Fig. 5). This relationship is important for FQ formation because FQs occur with less snow depth and more thaw days (Lacroix, 1980). As the total thaw days per winter season increases in Toronto, the number of days with no measurable snow cover on the ground within the same winter also increases implying a greater susceptibility in today's climate to ground recharge of liquid precipitation or surface water (i.e. snowmelt or flooding).

Since the frequency of air masses with milder air (as compared to drier air) has increased in recent decades in Toronto, and the likelihood for liquid precipitation to saturate the ground has increased (from an increase in thaw days and decrease in snow depth), FQs are more probable to occur in the early 21st century than the mid-20th century. Toronto and southern Ontario are still susceptible to dry arctic air mass outbreaks from the polar source regions as indicative of the recent two winters (2013/14, 2014/15) in which both seasons were considered two of the coldest periods on record (Battaglia and Changnon, 2016). The cold air masses that protrude into southeastern Canada can freeze the "trapped" water that saturates the ground and could cause FQs if the

Table 5: Pearson correlations and R^2 values for air mass types vs. thaw days ($T_{max} \geq 0$°C). Standard errors are provided in parentheses. [*Indicates statistically significant at confidence level of < 0.05.]

Air Mass Type	Thaw Days	R^2
DP	-0.25* (0.08*)	0.17*
DM	+0.41* (0.10*)	0.24*
MP	-0.31* (0.11*)	0.13*
MM	+0.18* (0.07*)	0.13*

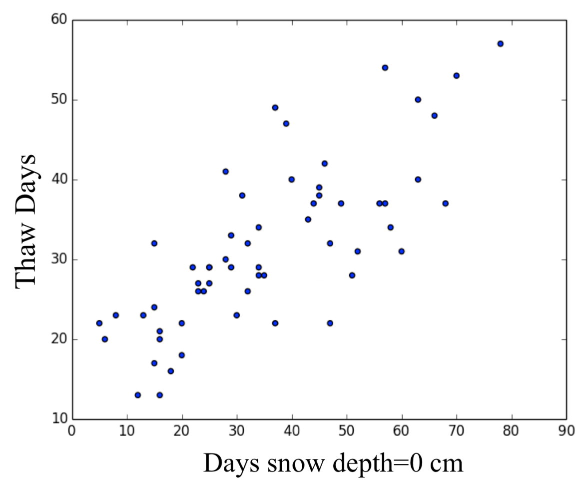

Fig. 5: Correlation between the number of thaw days and non-measurable snow depth days (= 0 cm) for Toronto for the 60-year period. The calculated R^2 is equal to +0.57.

surface temperature undergoes a rapid descent to well-below freezing.

4. Conclusions

Wintertime (DJF) air mass frequencies over a 60-year period for Toronto, Canada are investigated to determine if changes in large-scale atmospheric patterns have influenced surface meteorological characteristics necessary to produce frost quakes. Cold and dry (DP, MP) air mass frequencies are decreasing at the expense of warmer, more humid (DM) air. Dry polar air that is advected during the winter months, although still susceptible for Toronto's climate, is occurring less frequently today than a half-century ago. The number of thaw days (when the daily maximum temperature is $\geq 0°C$) in the winter has increased by approximately 14% inferring an incremental rate of one additional day, about every five winters, that reached thaw conditions.

The thaw environment allows for liquid precipitation or snowmelt from snow cover on the surface to saturate the ground and trap water in the subsurface more frequently. Snow depth plays a significant role in ground saturation during the wintertime in that little-to-no snow cover is necessary for a frost quake occurrence. An increase in the number of no snow depth winter days in Toronto is indicated from the relationship with an increase in thaw days. The rise in thaw conditions suggests that the meteorological characteristics required for frost quake events are more probable to transpire today.

The 2013/14 and 2014/15 winters comprised some of the coldest arctic air (i.e. DP air mass) outbreaks in the eastern two-thirds of North America in recent memory. These cold outbreaks, combined with the increase in the amount of saturated ground from thaw conditions, are the probable cause for the increase in frost quake episodes in recent winter seasons in southeastern Canada.

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